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Design, Development and Implementation of an Active Control System for Load Alleviation for a Commercial Transport Airplane

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Report No.683

DESIGN, DEVELOPMENT AND IMPLEMENTATION OF AN ACTIVE CONTROL SYSTEM FOR LOAD ALLEVIATION FOR A COMMERCIAL TRANSPORT AIRPLANE

by

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Paper presented at the 49th Structures and Materials Panel Meeting,
Porz-Wahn, Germany, October 1979.

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PREFACE

The Sub-Committee on Aeroelasticity of the Structures and Materials Panel has a permanent interest in all applications of active control technology that might help in improving the behaviour of the structure; load alleviation, flutter suppression etc. The very first application of the concept of manoeuvre load reduction to a large civil aircraft, with immediate interest to the airlines, is the system developed by Lockheed for the L-1011. In particular, certification problems had to be addressed by the firm, with the many new aspects introduced by the active control technology.

Mr O'Connell's presentation was very brilliant, and the Sub-Committee unanimously agreed that it should be published as an AGARD Report. This publication will certainly help the understanding of the possibilities and the difficulties that appear once active control technology leaves the comfort of experimental work and deals with large practical applications.

G.COUPRY
Chairman, Sub-Committee
on Aeroelasticity

CONTENTS

DESIGN, DEVELOPMENT AND IMPLEMENTATION OF AN ACTIVE CONTROL SYSTEM FOR LOAD ALLEVIATION FOR A COMMERCIAL TRANSPORT AIRPLANE

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SUMMARY

An active control system for load alleviation has been developed for a long-range version of the Lockheed L-1011. This system, which permits the use of an extended wing span for fuel conservation with minimum structural change, will be introduced into commercial service in early 1980. The system is described and the criteria to which it is designed are discussed. Examples of flight test data obtained from a prototype version of the system installed on the flight test airplane are presented, and comparisons of these results with analytical predictions are shown. A basis for certification of such systems is presented, assuring a level of safety equivalent to that of a conventional design.

INTRODUCTION

Lockheed-California Company has for many years conducted research in the area of active controls. Prior to 1974, however, the applications investigated were primarily concerned with flight-critical controls functions implemented by means of highly reliable active control systems. These applications required long-term development efforts and were largely associated with control configured aircraft of the future. In 1974, the emphasis of the active controls research activity shifted to applications of state-of-the-art systems to the present generation of wide-body commercial transports. Initially, these efforts took the form of providing a level of load alleviation which would permit increasing the gross take-off weight of an L-1011 derivative while minimizing wing structural changes. In mid-1975, an even more compelling objective was identified: wing span extension of the L-1011 in order to achieve improved fuel economy (Ref. 1, 2). As in the previous application, load alleviation through the use of active controls is used to minimize wing structural changes. A breadboard active control system was developed to assess the feasibility of this objective, and the system was flight tested under funding from the NASA Aircraft Energy Efficiency program beginning in mid-1977 and extending through 1978. The results of these research activities (Ref. 3) were so uniformly encouraging that the concepts were incorporated in an advanced design configuration early in 1978. The resulting production configuration will be certificated early in 1980 and will enter commercial service shortly thereafter. It is this production program which is the subject of the present paper.

DESIGN CRITERIA

The primary design objective of the active control system (ACS), as indicated earlier, is to minimize structural changes to the L-1011 wing resulting from the wing span extension of nine feet (Fig. 1). The effect of this span extension is to increase both the maneuver loads and gust loads imposed on the wing, which in a conventional design might

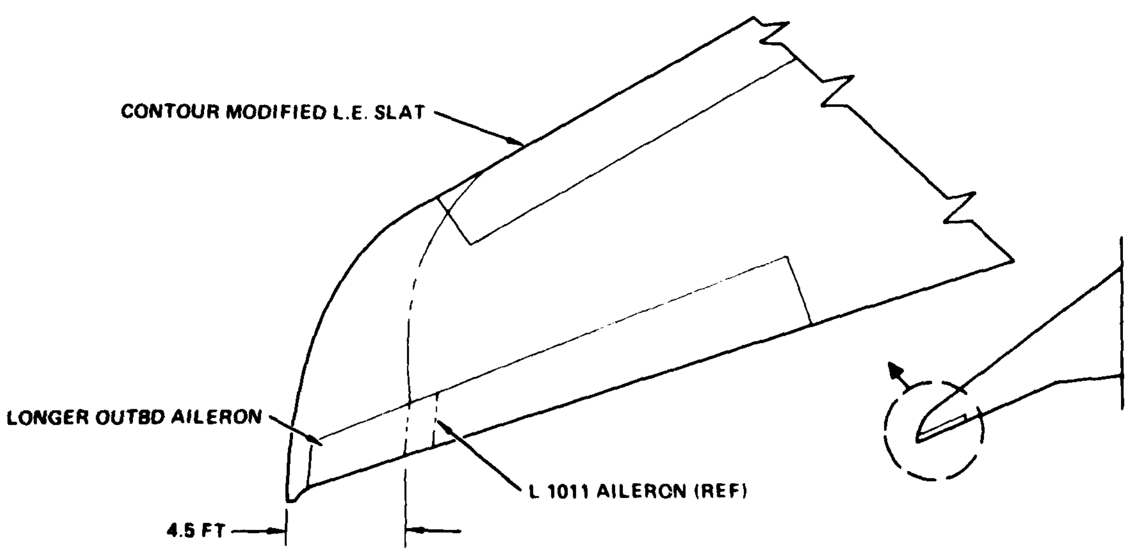

Figure 1. Extended Span Wing

require the structural redesign of major portions of the wing. To minimize the extent of this redesign, the maneuver load and gust load increments resulting from the span extension must be eliminated or greatly reduced by the active control system. In accomplishing this reduction of loads, a further requirement of the ACS is that the stability, control, and handling qualities of the basic airplane must remain substantially unchanged. In addition, the modal response characteristics of the airplane must either be unchanged or must remain within acceptable limits.

The primary area to be addressed by the design criteria, however, concerns the reliability of the ACS and the consequences of the fact that the system will be unavailable in flight a small percentage of the time. Since the ACS is employed to reduce the design flight loads of the wing, it is clear that some reduction of capability to sustain maneuvers and gusts exists during the time the ACS is inoperative. At the same time, criteria adopted at Lockheed required that the airplane with ACS demonstrate the same level of safety as that of a conventionally designed airplane. One obvious way to achieve this is to employ an ACS so reliable that the failure of the system need not be considered. Most regulatory agencies quantify this in terms of a probability of failure of 10^{-9} or less per flight hour. Although such systems are conceptually possible, and research and development of such systems is in progress, they are not likely to be available until some time in the 1990's (Ref. 4). To make use of active systems which are presently feasible, and which incorporate portions of existing systems on current commercial transports, probabilities of system failure in the range of 10^{-6} to 10^{-3} per flight hour must be accommodated. The lower end of this range would be representative of systems having maximum redundancy levels, while the upper end of this range would apply to such systems in lower states of redundancy due to one or more system faults. In view of this, it is clear that the required level of safety cannot presently be assured by means of increased system reliability alone. Another approach must be adopted.

The method of assuring an equivalent level of safety to that of conventional design practices may be discerned by examining the procedure for developing gust loads resulting from the response of the airplane to continuous turbulence (Ref. 5). In this procedure, the significant response (load) quantities are analyzed to determine the frequency distribution of peak response levels. From these data, the relationship between the level of the response quantity and the frequency of exceedance of that level is determined. This done, the selection of an acceptable frequency of exceedance of limit load then determines that load. The analysis which derives the frequency of exceedance of the various response quantities considers all those parameters which influence the responses: airplane configuration, flight condition, weight, center-of-gravity location, etc. The variation of these parameters is represented by performing the analysis for a large number of combinations of these parameters, and associating the appropriate percentage of the total airplane operational time with each combination. It is a logical extension of such an analysis to include the functional state of the ACS as an additional parameter, once the expected rate of system unavailability is known. The effect of system unavailability on gust loads is to increase the frequency of exceedance of given levels of certain of these loads, requiring the selection of higher design limit levels of these loads in order to maintain the same frequency of exceedance as for conventional designs. One requirement for the establishment of equivalent safety is then: the frequency of exceedance of design limit load shall be no greater for the airplane designed with the ACS than for a conventionally designed airplane.

Although the procedure described above adequately provides for the determination of the effect of system reliability on gust loads, it cannot be applied in the same manner to maneuver loads. The determination of limit design maneuver loads has traditionally been based on deterministic criteria using design envelope conditions rather than typical operating conditions. Not only is there no general acceptance of a probabilistic approach to the determination of maneuver loads, but also there exists no body of data on conventionally designed airplanes which may be used to determine an acceptable frequency of exceedance of design limit load. To adhere more closely to the deterministic traditions in the formulation of maneuver loads, the equivalent safety requirement is revised to state that the frequency of exceedance of limit maneuver load factor, in any given design-envelope flight condition, will be no greater than for a conventionally designed airplane. This leads to the procedure illustrated in Fig. 2 and explained in detail in Ref. 6, wherein NASA maneuver acceleration data are used to determine design limit load factors for system on and system off which will result in a combined frequency of exceedance equal to that associated with a load factor of 2.5. In this example, the in-flight availability is assumed to be 99.9 percent and a system-off limit load factor capability of 1.8 is used, giving a system-on design limit load factor of 2.54. It should be noted that the results obtained are not sensitive to the absolute level of the frequency of exceedance data, but are dependent on the shape of the frequency of exceedance curve. This sensitivity may be accommodated by applying a reasonable tolerance in fitting the data. In passing, it should be mentioned that the frequency of exceedance of 3.2×10^{-5} per flight associated with a load factor of 2.5 in Fig. 2 is roughly equal to the 2×10^{-5} per flight hour frequency of exceedance used in the determination of design limit gust loads. The corresponding frequency of exceedance of limit maneuver load, considering typical operating conditions, would be in the 10^{-7} to 10^{-8} per flight hour range. Using this same exceedance curve, and still assuming an in-flight availability 99.9 percent, the locus of load factor pairs resulting in equal frequency of exceedance is determined (Fig. 3). It will be seen that the effect of system unavailability is to increase the system-on design limit load factor to compensate for the increased frequency of exceedance of limit load factor during the time the system is inoperative. A

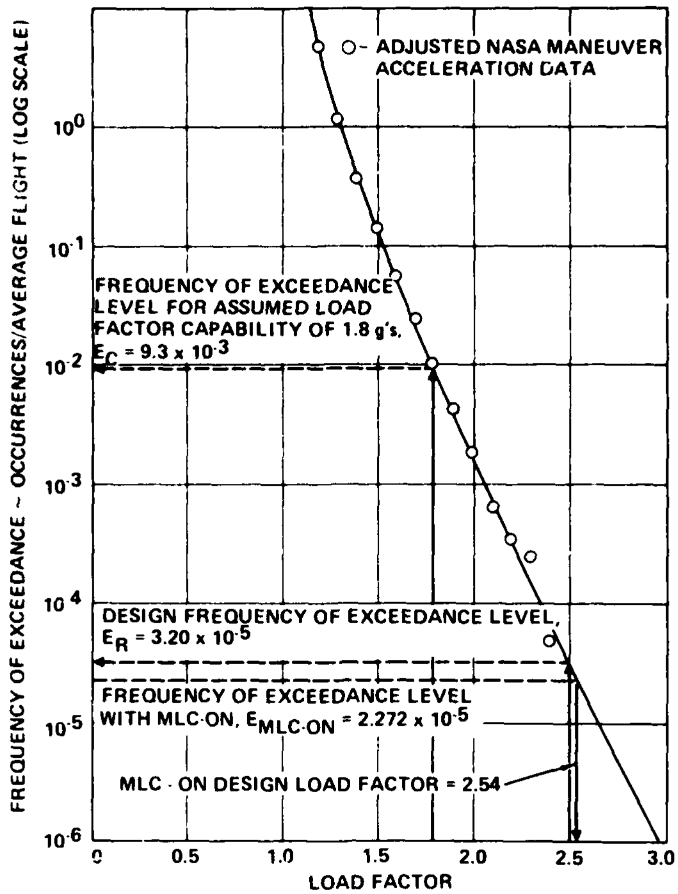

Figure 2. Example of Accounting for MLC System In-Flight Availability in Determining Design Maneuver Loads

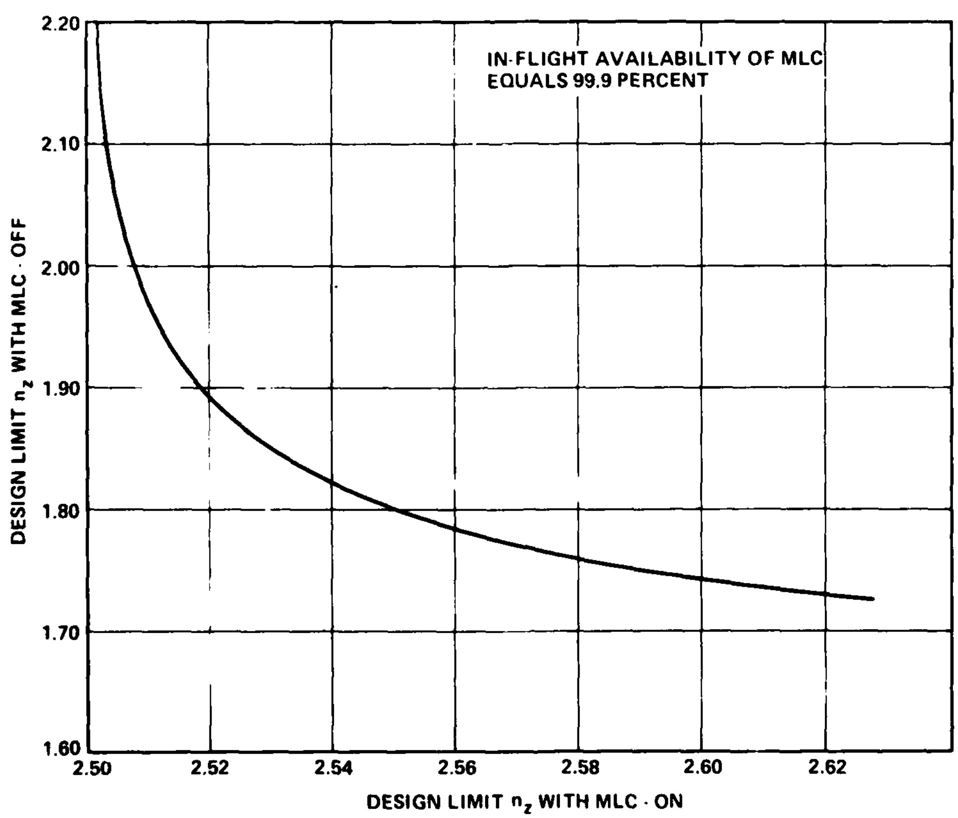

Figure 3. Limit Design Load Factor MLC-ON vs MLC-OFF

further result is to impose an effective lower limit on the system-off design limit load factor which may be used in conjunction with a given system availability. Curves for other values of system availability are shown in Ref. 6.

Once an equivalent frequency of exceedance of limit load, or limit load factor, is assured, the behavior of the system in response to parameters above limit must be examined. For the equivalent safety concept to extend to the region above limit load, a further requirement must be imposed on the airplane designed with the ACS. This may be stated that, for the airplane designed with ACS, the margins above the limit load level will be essentially as great as those for a conventionally designed airplane. Since the ACS has limited control surface deflection and rate capabilities, as do all such systems, the effect of these nonlinearities on the margins above limit load must be determined.

The limitation of control surface deflection primarily affects maneuver loads and gust loads in the low frequency region. The effect on maneuver loads will be illustrated although the effect on gust loads is comparable. The case of the conventionally designed airplane is represented by the solid line relating load factor to relative stress in Fig. 4. Limit load corresponds to a load factor of 2.5. Ultimate load is taken as 150 percent of this value and, in the case shown, results in an ultimate load factor capability of 3.75 on a linear basis. The airplane designed with ACS is represented by the dashed line which intersects the solid line at a load factor of 1.0. As can be seen, the slope of the line is reduced, such that the load at limit load factor is 30 percent less than for the airplane without ACS. This lesser value, increased by the 1.5 factor of safety, becomes the design ultimate load for the airplane with ACS. Above limit load, the slope remains constant until the authority limit of the system is reached at a load factor corresponding to 20° of surface. At this point, the slope of the load versus load factor line becomes equal to that of the airplane without ACS. The result illustrated here, showing approximately equivalent margins of safety, is typical of the design loads of the L-1011. As indicated in Ref. 6, however, the results may be configuration dependent, and should be evaluated for the particular case of interest.

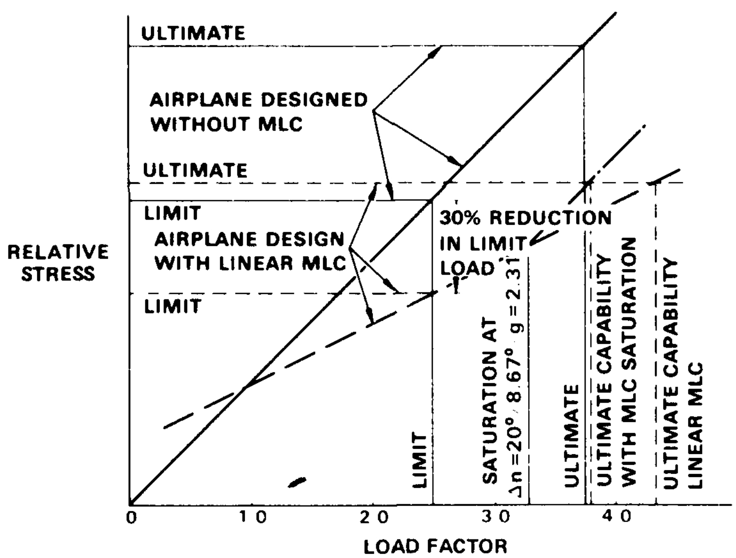

Figure 4. Typical Effect Of MLC Saturation On Ultimate Maneuver Load Capability

The effect of the limitation of control surface rate, which primarily influences gust loads at the airplane elastic mode frequencies, is much more difficult to determine. A nonlinear analysis must be performed to determine this effect, and the loads derived from the linear analysis increased to compensate for it.

SYSTEM DESCRIPTION

General

During the early research investigations of the active control system, the use of each of the existing control surfaces of the L-1011 was considered as a candidate for wing load alleviation. As might be expected, the inboard ailerons were soon eliminated as candidates due to the relative ineffectiveness of these surfaces in influencing wing loads. The outboard ailerons and the all-movable horizontal stabilizer were selected for further evaluation. Using these surfaces, maneuver load control (MLC), elastic mode suppression (EMS), and gust load alleviation (GLA) functions were investigated in depth. Analytical investigations indicated the MLC and EMS functions, implemented by means of the outboard ailerons, to be very effective in reducing wing loads. The GLA function utilized the horizontal stabilizer to reduce wing loads resulting from the response to turbulence of the airplane in the short period mode; analysis indicated this function to be only marginally effective. In this phase of the investigation, it was anticipated

that the use of the stabilizer would be required to offset the pitching moment introduced by the outboard ailerons as a result of the MLC function. Since this would require an active stabilizer in any event, the retention of the GLA function could be justified. A breadboard active control system incorporating these three functions was designed, fabricated, and tested in the laboratory. At this point, Lockheed obtained the support of the NASA Aircraft Energy Efficiency program in the form of a research contract to perform the flight test evaluation of the breadboard system (Ref. 3). During this same period, it was anticipated that the wing span extension of the L-1011 might reduce flutter margins of the airplane to an unacceptable level. As a result of this, investigations were also conducted to determine the feasibility of employing active controls for flutter margin augmentation (FMA). These investigations, detailed in Ref. 7, included the design, fabrication, and flight testing of three candidate systems. Two of these systems made use of the outboard ailerons, with the third system being implemented through the use of the horizontal stabilizer. The FMA system block diagram is shown in Fig. 5. As detailed in Ref. 7, the candidate system which produced motions of the outboard ailerons as a function of wing tip accelerations proved to be the most effective in flight test. When flight test results with the extended span configuration were available late in 1978, however, it was determined that an FMA function was not required. At the same time, assessment of the handling qualities of this configuration indicated that the effects of the pitching moment introduced by the MLC were nearly offset by the increased stability of the extended span. Since pitch compensation through the active stabilizer was therefore no longer a requirement, retention of the marginal GLA function could not be justified.

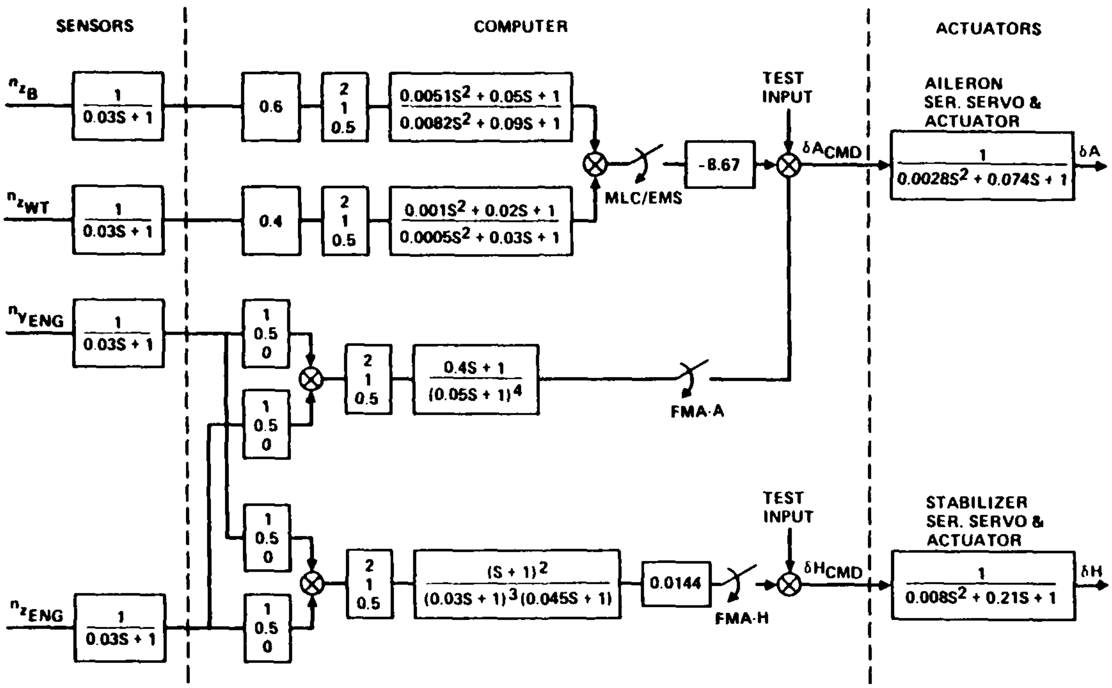

Figure 5. FMA Analog System Block Diagram

Production ACS

The resulting production configuration of the ACS incorporates the MLC and EMS functions only. The location of the principal system components is shown in Fig. 6 and the functional block diagram is given in Fig. 7. From these illustrations, it can be seen that signals are generated by vertical accelerometers in each wing tip and the fuselage and are input to the computers. The computers perform the control law computations and other prescribed functions and output voltage commands to the outboard aileron series servos, which in turn superimpose symmetric aileron inputs on the roll control inputs from the inboard ailerons. The gain scheduling indicated in Fig. 7 utilizes signals from the speed sensors shown in Fig. 6 and from switches indicating the position of the flaps.

Control Law and Computer

The relationship of the sensor input signals to the series servo voltage commands is determined by the control law, or filter, programmed in the computer. This relationship must be such as to provide the required aileron motions in response to acceleration signals, considering the characteristics of the sensors, series servos and power servos. The aileron motions required for the MLC and EMS functions are quite readily determined: for a quasi-steady 2.5g symmetric maneuver, an aileron trailing edge up deflection of 15 degrees with minimum phase lag is required, and for the 1.5 to 1.8 hertz region of the first wing bending mode an additional 90 degrees of phase lag and

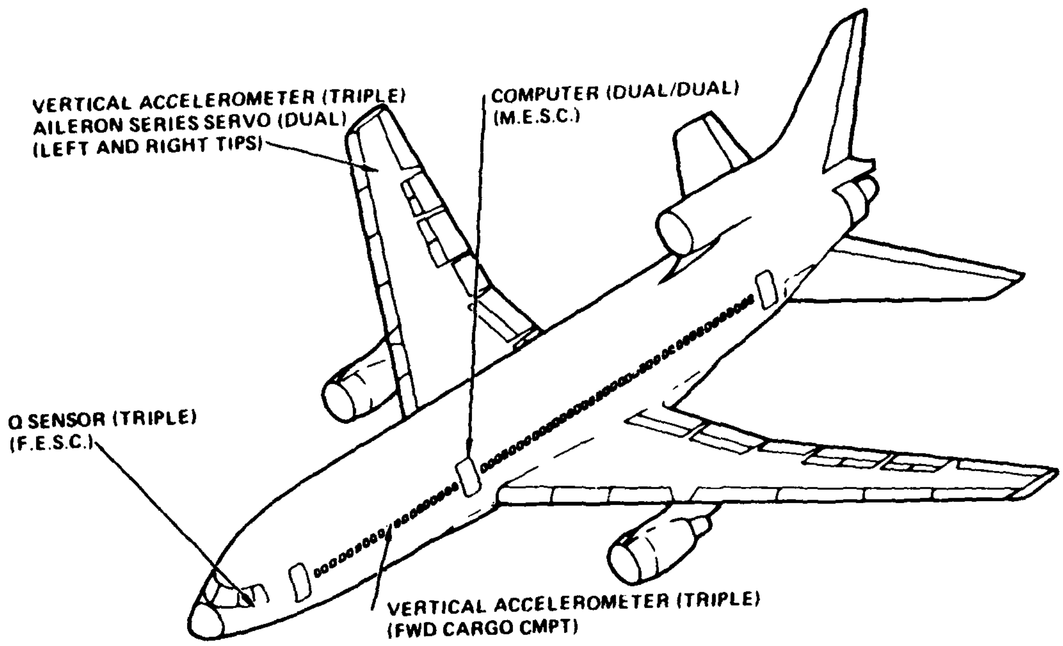

Figure 6. Location of Principal ACS Components

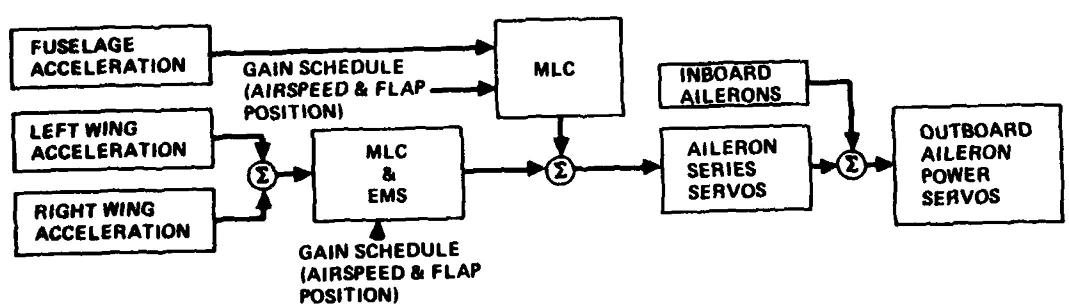

Figure 7. ACS Functional Block Diagram

reasonably high gain must be provided. In addition to these characteristics, adequate gain and phase margins must be provided for all the significant modal responses of the airplane. It is this latter requirement which results in a much greater complexity of the control law than would result from the primary functional requirements alone. Since the specific control law characteristics are so highly configuration dependent, they will not be discussed in detail here. It may be of interest to indicate, however, the procedures used to derive these characteristics. For the frequency range of 0-5 hertz, the control law characteristics derived by analysis required little or no modification as a result of the flight test program. This frequency range included first and second wing bending, stabilizer first bending, fuselage first bending and engine-pylon vertical and lateral bending. In the 5 - 10 hertz range, the analysis provided useful guidance in the development of the control law, but significant adjustments were required in order to incorporate flight test results. The control law characteristics above 10 hertz were dictated almost entirely by test results.

The ACS computer is a four channel or dual-dual digital computer utilizing CAPS-6 (Collins Adaptive Processing System) processors. The computer is described in detail in Ref. 8, and therefore the present discussion will be limited to a few of the outstanding features of the system. One of the foremost of these is the facility with which control law changes can be implemented. Considering the extent to which control law changes were dictated by test results in the later phases of the program, it is doubtful that schedules could have been met without this capability. A second important feature is the very extensive system monitoring which is performed by the computers. This monitoring is capable of detecting faults in the sensors, sensor signal channels, series servos and the computational channels, and to reconfigure the system if conditions for continued operation exist. This capability leads to a third important feature of the system, which is that extensive fault isolation and identification is provided. When a fault in the system occurs, the presence of the fault is annunciated in the flight station, and data identifying the faulty line replaceable unit (LRU) is stored in the computer. Maintenance personnel can later interrogate the ACS computer, which then displays the identification of the faulty LRU's.

System Availability

The system in-flight availability requirements discussed earlier are met or exceeded by the architecture indicated in Fig. 6 and 7. The sensor sets are triply redundant, with any two sensors of a given set required for operation. The computers are dual, with each computer having two identical channels. Dual series servos are provided for each aileron, with one servo for each aileron being required for operation. This level of redundancy results in a probability of failure of the basic system (with no faults present) of well below 10^{-5} per flight hour. With a first fault present, the probability of system failure ranges from a value slightly greater than 10^{-7} per flight hour to a value slightly less than 10^{-3} per flight hour, depending on the particular fault. As can be seen, the structural design requirement of 99.9 percent in-flight availability will be easily exceeded for even extended operations with a first fault present.

TEST RESULTS

Results of the laboratory, ground and flight tests of the ACS are presented and discussed in detail in Ref. 3; selected elements of the flight test results are presented here to illustrate the extent of these tests.

Maneuver loads data were obtained by performing wind-up turns and roller coaster maneuvers with system on and system off, and determining various load parameters as a function of vertical load factor. Shown in Fig. 8 are the shear, bending moment and torsion at an outboard wing station obtained from roller coaster maneuvers at 379 KEAS. Also shown are the analytically predicted increments at a load factor of 1.6. Note that whereas the slope of bending moment and shear versus load factor are reduced by the ACS, the slope of torsion versus load factor is increased. This latter result was adequately predicted by analysis, and required a modest increase in strength of the outer wing spar webs. Another measure of the maneuver loads reduction achievable by the ACS is given by the spanwise distribution of bending moment due to outboard aileron deflection shown in Fig. 9. The test data were obtained by measuring load quantities at several spanwise stations in level, trimmed flight for a range of aileron deflections. Data for three airspeeds are presented and compared with analytical predictions

A series of tests which proved to be extremely useful in validating the dynamic characteristics of the ACS, as well as those of the mathematical model of the airplane, measured various load and motion parameters in response to control surface oscillatory inputs. The open-loop response data, samples of which are shown in Figs. 10 and 11, are compared with analytical results and are used to substantiate the validity of the mathematical models. Open and closed loop response data, such as that shown in Fig. 12 along with the analytical predictions, are used to validate both the mathematical models and the ACS performance in the elastic mode region.

In an attempt to obtain a direct measure of the ACS performance in the reduction of gust loads, flight test data were obtained for the airplane in turbulence, both system on and system off. The airplane was equipped with a gust boom, enabling the measurement of gust velocity at the airplane centerline. Turbulence response time histories were obtained for a large number of parameters of interest, and these data

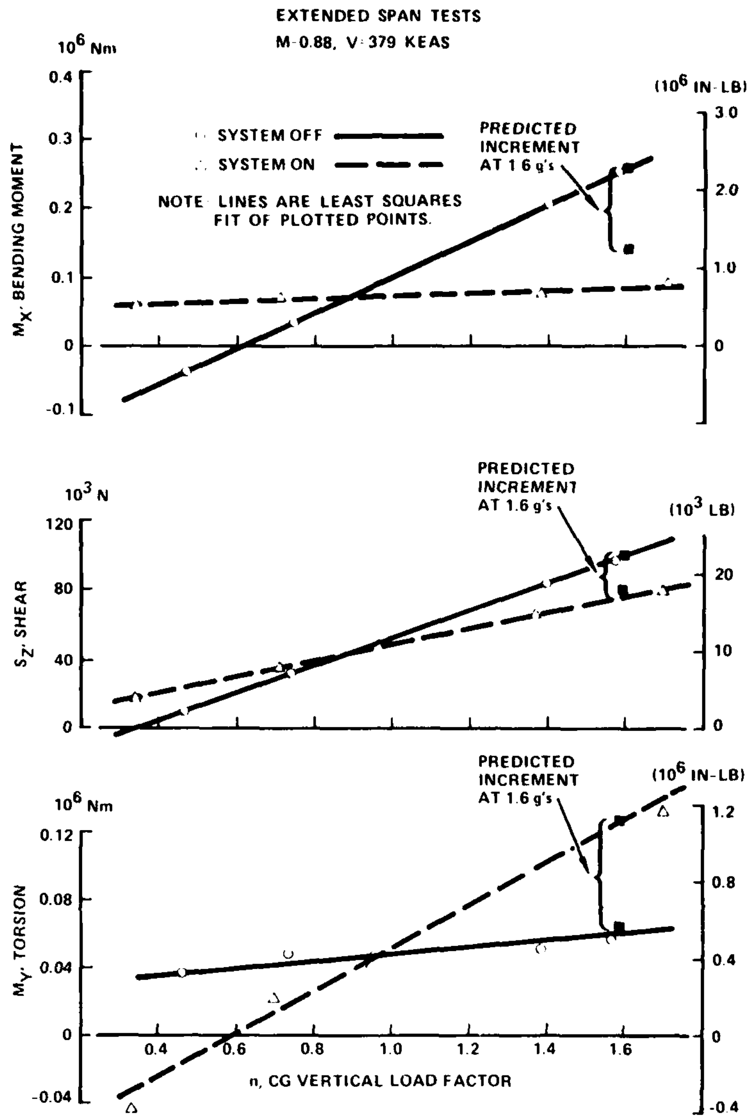

Figure 8. η = 0.71 Bending Moment, Shear and Torsion vs. Load Factor

were processed to obtain power spectral density (PSD) plots and values of the response parameter $\bar{A}$. A complete description of the test results and analysis procedures is presented in Ref. 3, as well as a comprehensive discussion of the results. All that will be attempted here is to indicate the types of data and results which were obtained. Shown in Fig. 13 is a PSD plot of the measured gust velocity for one burst of turbulence, compared with theoretical distributions. A PSD plot of wing bending moment at an inboard wing station is shown in Fig. 14, and PSD plots of wing bending moment normalized to gust input are given in Fig. 15 and 16, for system on and system off. On these latter plots, PSD's obtained from a recently developed three dimensional gust analysis procedure are included. Comparisons of ACS load reductions obtained from theory and test data are presented in Fig. 17 and 18. On these summary plots, the dashed line represents the locus of equal test-theory load reductions.

Certification Criteria

The philosophy of equivalent safety, discussed earlier, provides an entirely adequate basis for certification of active controls. This approach interrelates system-on design loads, system-off design loads and system reliability in such a way that, as the load alleviation function becomes increasingly more flight critical, an increasing level of system reliability is required. This is illustrated in Fig. 19, where system-off design load factor is shown as a function of average system unavailability, when system-on design load factor is held constant at 2.53. All points along the curve represent designs of equal safety. One difficulty with this approach, in terms of substantiating the safety of a particular design to the regulatory agencies, lies in the factors which determine average system unavailability. This parameter is dependent on the length of time the ACS is permitted to remain in operation with an initial fault, which is in turn a function of

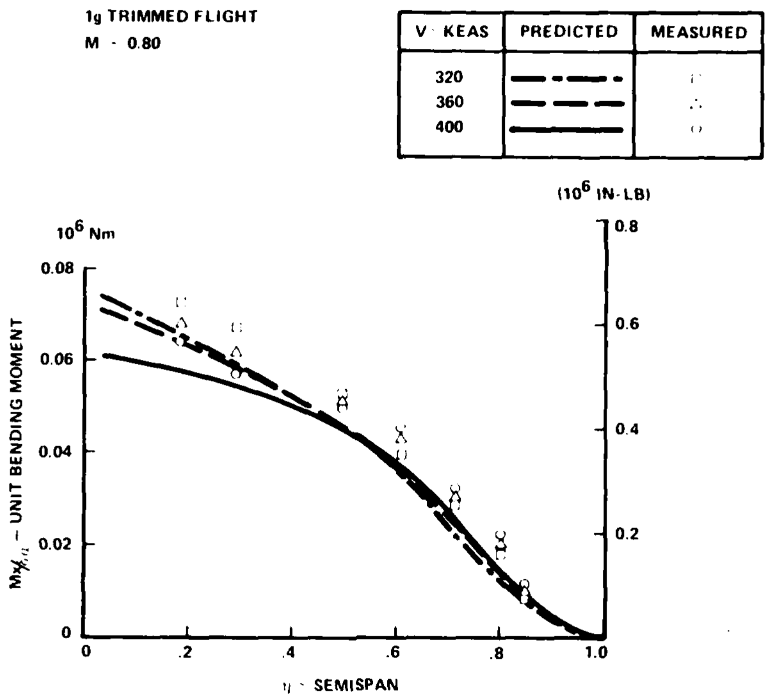

Figure 9. Unit Outboard Aileron Bending Moment

the maintenance practices of individual airlines. Although this variability can be compensated for by the use of very conservative assumptions in deriving the availability parameter, regulatory agencies are reluctant to incorporate these assumptions as part of the certification basis. In response to these concerns, Lockheed and McDonnell-Douglas have separately proposed alternate criteria based on probability of system failure. A composite of these proposals is shown in Fig. 20, which defines system-off design ultimate loads, with and without fail-safe structural damage, as a function of probability of system failure. These criteria are somewhat arbitrary, and considerably exceed the equivalent safety criteria represented by Fig. 19. They do, however, have the advantage of being based on the probability of failure of any particular system configuration for which certification is requested; this parameter can be controlled and substantiated in the design process. In any event, it is important that such criteria be expressed as continuous functions of failure probability, so that improved systems may be accommodated by the criteria as they evolve.

With the above discussion in mind, it should be noted that there is a tendency to prescribe a design floor for system-off capability. This procedure effectively limits the peak risk incurred when the system is inoperative, and it is clear that the values proposed for this minimum capability present no undue constraint on the design of today's active control systems. The procedure will just as effectively inhibit the development of future systems, however, unless the design floor is in turn a function of system reliability - resulting in a continuous function such as that expressed by Fig. 20.

Conclusion

The active control system for load alleviation described in this paper achieves all of the design objectives established for it while utilizing state-of-the-art systems technology. The requirements imposed on the system are realistic ones which can readily be met in the airline operations environment; no unusual or time-consuming maintenance practices are required. The design criteria imposed on the system are such as to assure that the level of safety will not be reduced relative to that of conventional design. In all respects, then, the active control system for load alleviation has achieved a state of readiness for introduction into commercial service.

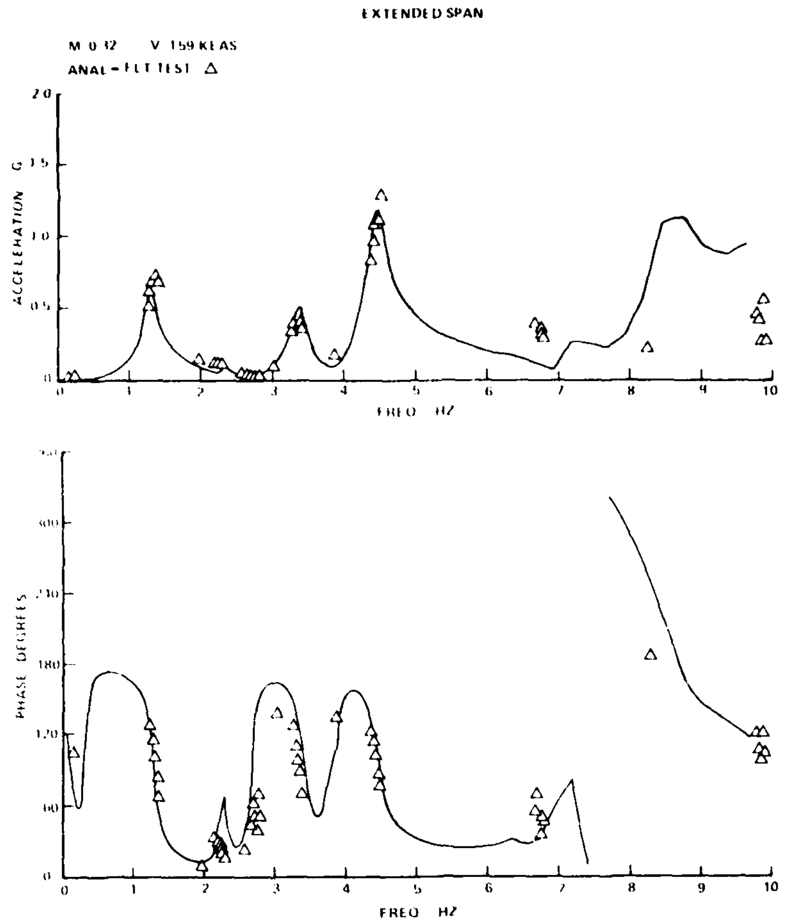

Figure 10. Wing Tip Normal Acceleration/Degree Aileron Open Loop

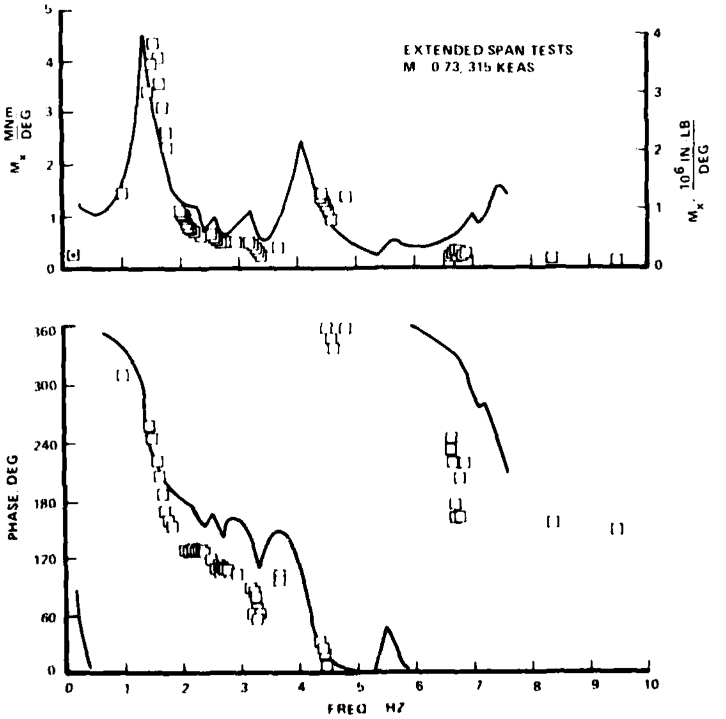

Figure 11. Test/Analysis, Bending at η = 0.19, Aileron Drive, Open Loop

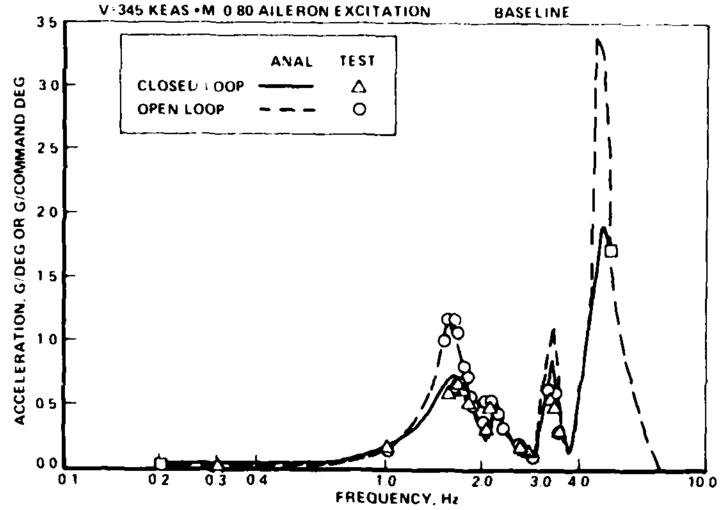

Figure 12. Wing Tip Normal Acceleration Per Degree Aileron, ACS On and Off

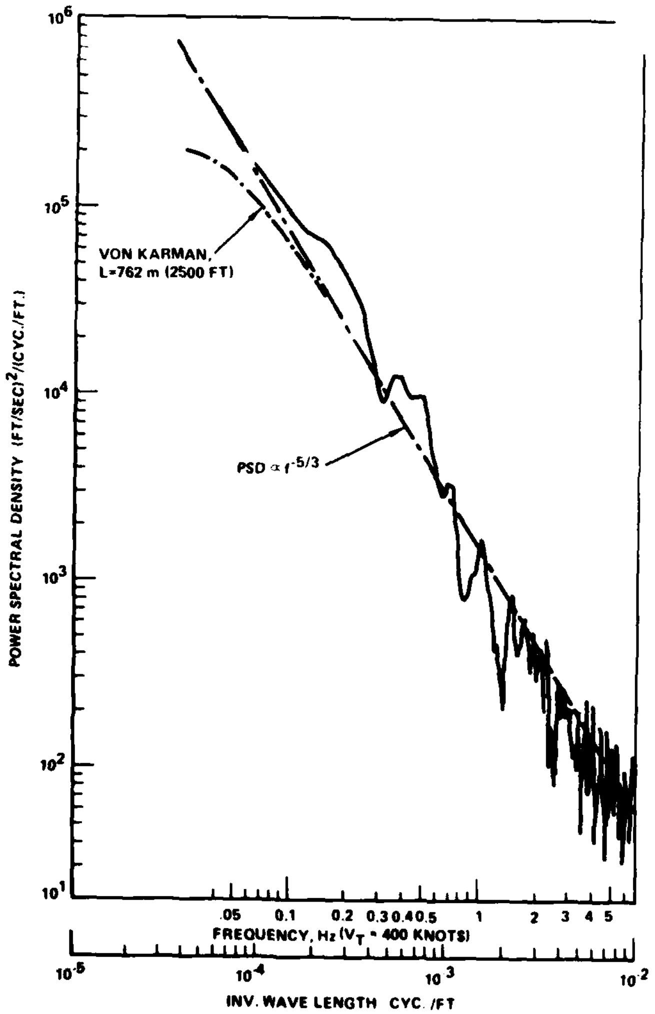

Figure 13. Gust Velocity PSD, Burst 3A

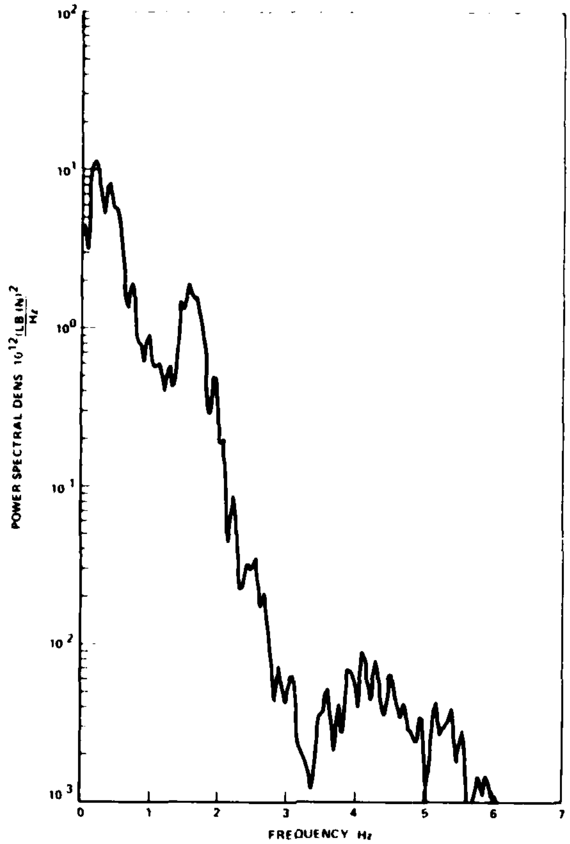

Figure 14. PSD Wing Bending at η = 0.29, Burst 3A

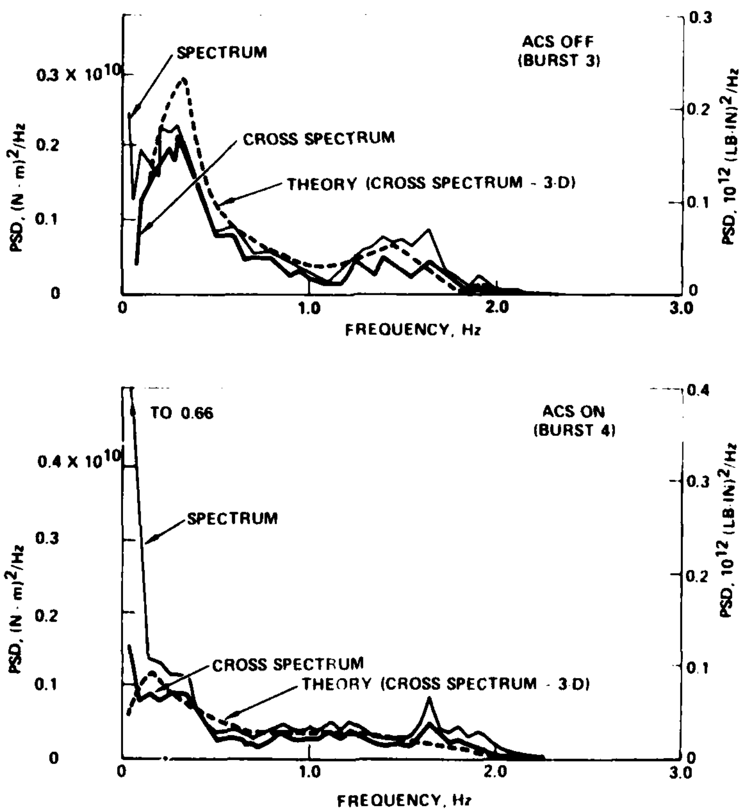

Figure 15. PSD of Wing Bending at η = 0.29 - Bursts 3, 4

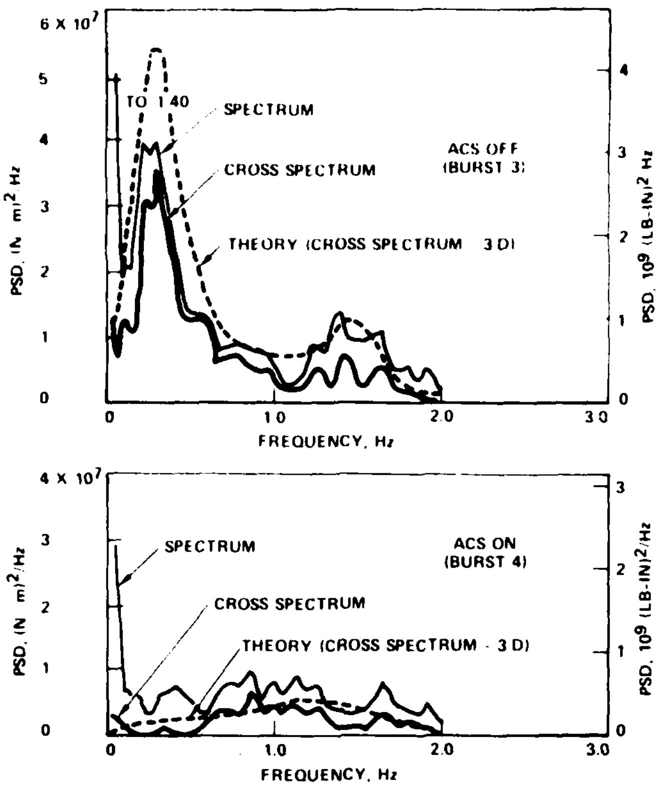

Figure 16. PSD of Wing Bending at η = 0.71 - Bursts 3, 4

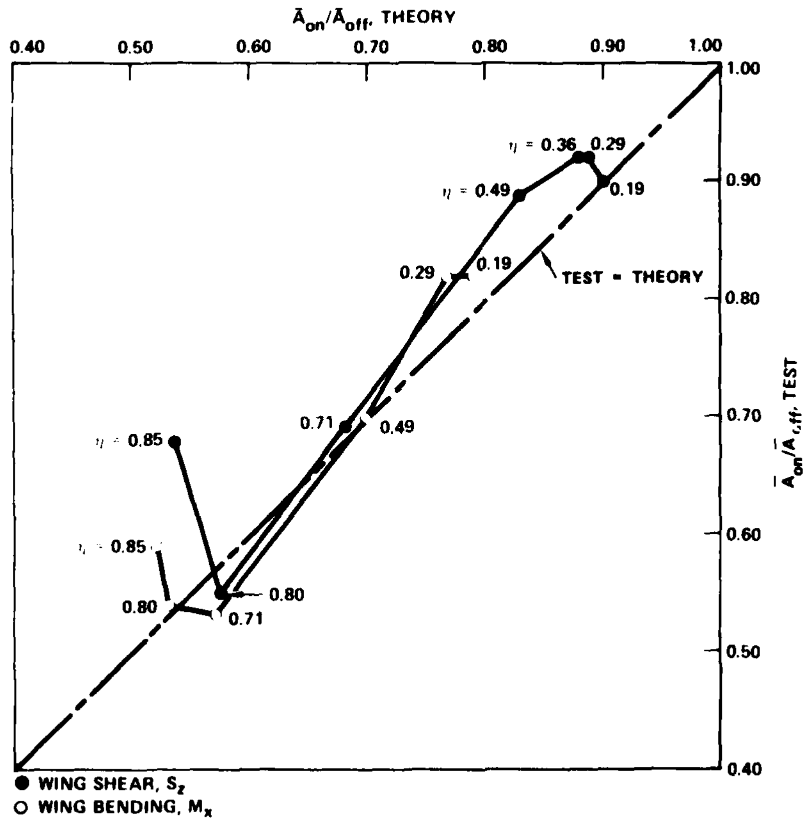

Figure 17. Load Reduction Due to Active Controls - Cross Spectrum Method, 1-D Theory - Bursts 3 and 4

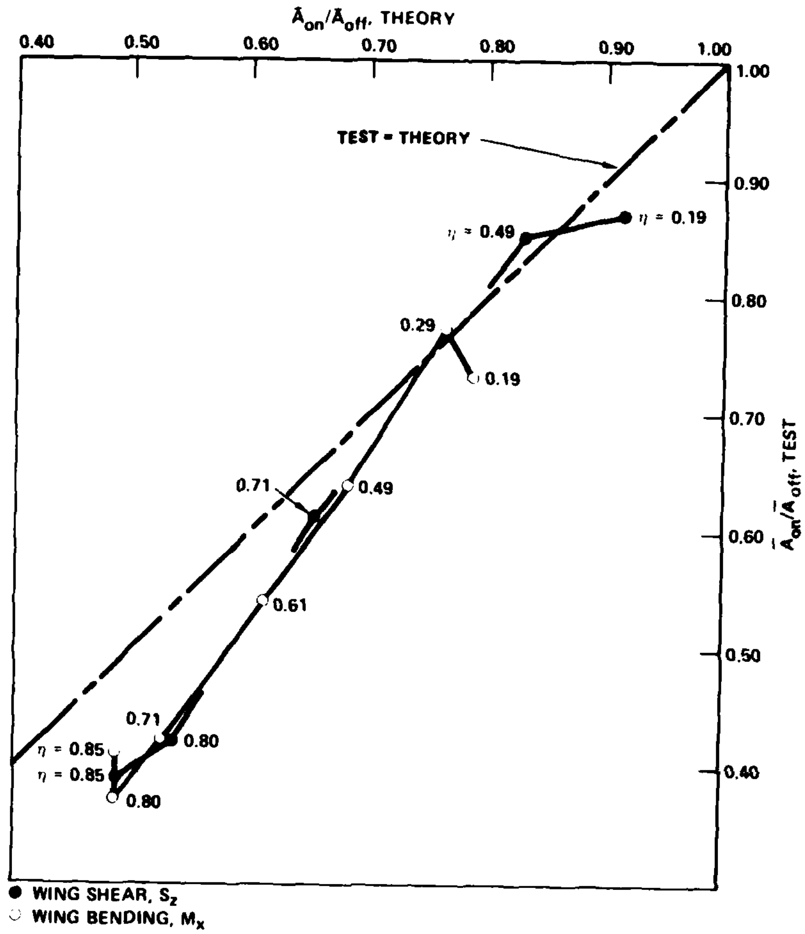

Figure 18. Load Reduction Due to Active Controls - Cross Spectrum Method, 1-D Theory - Bursts 5 and 6.

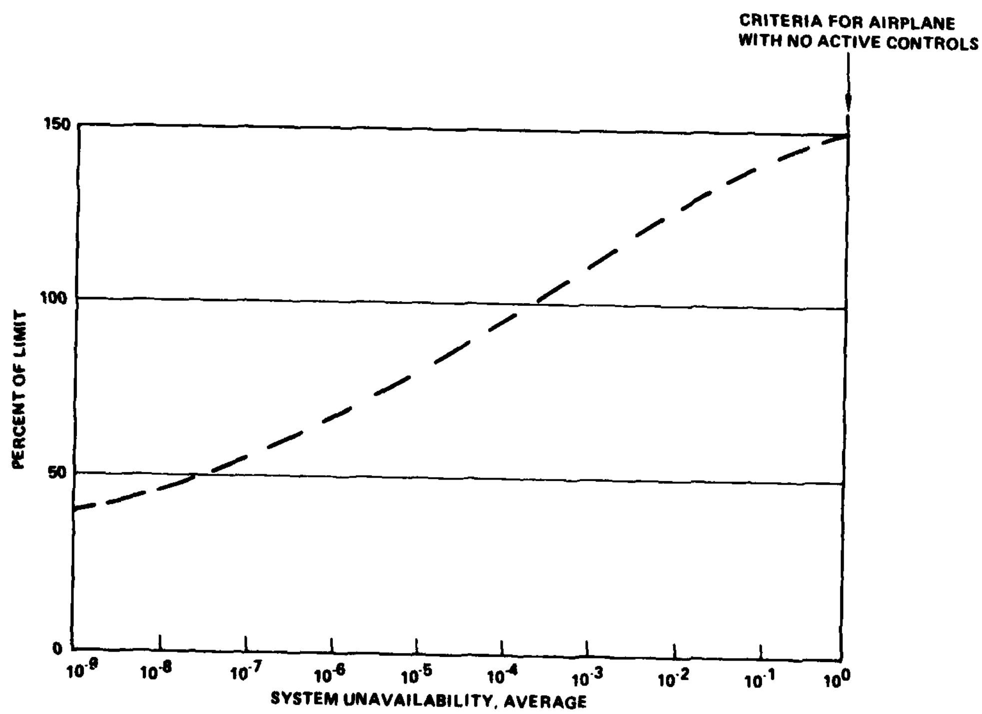

Figure 19. Design Ultimate Loads for Failed Active Control System, Equivalent Safety

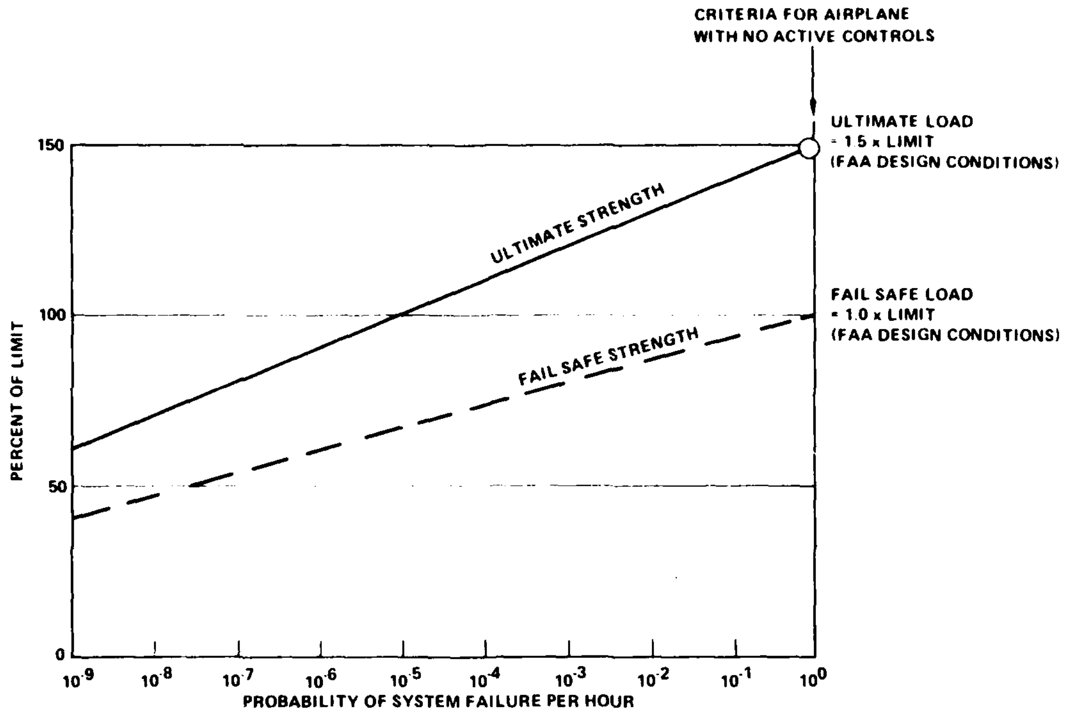

Figure 20. Design Ultimate Loads for Failed Active Control System, Proposed Criteria

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14. Abstract

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